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A high contrast 12.6 keV Kr Kα source has been demonstrated on the petawatt-class Titan laser facility. The contrast ratio (Kα to continuum) is 65, with a competitive ultra short pulse laser to x-ray conversion efficiency of 10^{-5}. Filtered shadowgraphy indicates that the Kr Kα and Kβ x-rays are emitted from a roughly 1 x 2 mm emission volume, making this source suitable for area backlighting and scattering. Spectral calculations indicate a typical bulk electron temperature of 50-70 eV (i.e. mean ionization state 13-16), based on the observed ratio of Kα to Kβ. Kr gas jets provide a debris-free high energy Kα source for time-resolved diagnosis of dense matter.

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I. INTRODUCTION

High energy density physics experiments frequently utilize x-ray probing of dense plasmas. These experiments use photons or particle beams to heat matter to solid density and higher, requiring a bright source of relatively hard x-rays ($E > 10$ keV) to adequately penetrate the plasma [1]. Two typical x-ray diagnostics are radiography [2] using an area backlighter [3] and x-ray Thomson scattering [4–6]. For both applications, it is important to develop intense, narrow bandwidth x-ray sources to yield a sufficient ratio of the scattering or transmission signal to the background (including continuum) radiation. Kα x-ray sources are spectrally narrow and are emitted over only several ps [7] even for extended sources [8], making them well-suited for both backlighting and scattering. High dynamic range scattering data require a high contrast ratio (the ratio of the Kα line intensity to the continuum intensity), which has been difficult to achieve in mid and higher Z Kα sources [9].

In the work presented here, we show that Kr gas jets irradiated by ultra short laser pulses are high contrast, debris-free extended sources of Kα x-rays at 12.6 keV with competitive conversion efficiency and narrow bandwidth. The contrast ratio is 65, a factor of 4 higher than the value previously measured for foils of similar Z [9] and the conversion efficiency (from laser energy to x-ray energy) is 2×10^{-5}, in the range previously measured [1]. Bandwidth of the Kα line is $\Delta E/E = 2\times10^{-2}$, sufficient for Thomson scattering in the Compton regime [10], from a source that measures roughly 1 $\times$ 2 mm. We also have investigated the plasma parameters (density, temperature, and ionization state) for a fuller description of the source.

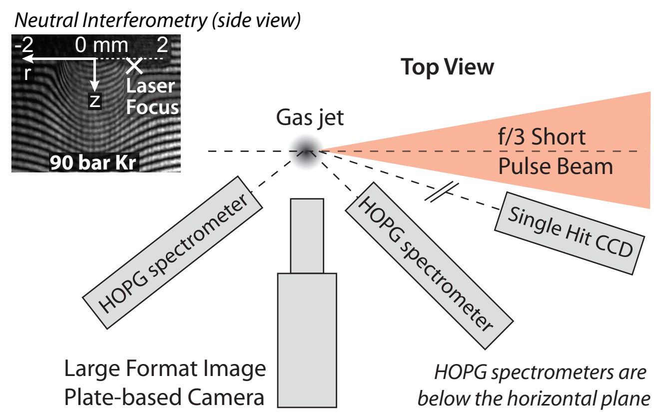

FIG. 1: (Color online) Top view of the experimental setup (the gas jet fires into the page) and neutral density interferometry (inset).

II. EXPERIMENTAL SETUP

We used the petawatt-class Titan laser facility at the Lawrence Livermore National Laboratory to produce Kr Kα x-rays. The Titan short-pulse beam delivers a maximum of 400 J of 1054 nm light in 0.4 ps, for up to 1 petawatt of power. A long pulse beam is also available for up to 1 kJ of 1053 nm light in nanosecond-length pulses. Short pulse focusing is achieved with an f/3 off-axis parabola to a $1/e^2$ spot diameter of 15 μm, giving a typical short pulse laser intensity on target above 10^{20} W/cm^2.

The laser was focused onto a super sonic Kr gas jet controlled by a solenoid valve that was pulsed on 10 ms before the laser pulse arrived. We focused the laser close to the gas jet nozzle and near the front edge of the gas jet (z = 0.2 mm and r = 1.2 mm, respectively, as seen in

Fig. 1) in order to maximize conversion efficiency [11]. Backing pressure was kept at 90 bars to ensure efficient laser absorption. High backing pressure causes clustering of the Kr gas into solid-density particles due to the adiabatic expansion of the gas, and clustering gas jet targets can absorb $> 95\%$ of the incident laser light [12]. A Lloyd's mirror interferometer [13] was used off line to measure the neutral density of the Kr gas jet. Abel inversion analysis indicated a neutral density of $8.7\times10^{19}\mathrm{cm}^{-3}$ $\pm10\%$ on axis at the nozzle exit. The gas jet nozzle was a conical super sonic nozzle with $d_{\mathrm{exit}} = 2$ mm, throat diameter $d_{\mathrm{crit}} = 1$ mm and an expansion length of 6 mm.

A single hit counting CCD [1, 14] captured broad bandwidth time integrated x-ray spectra. This well-established technique uses a CCD camera placed far enough away from the x-ray source that a series of single photon events are recorded on the detector. Single event histogram binning [14] of the image yields an absolute number of photon events at discrete energies. In our setup, the single hit CCD observed the front side of the gas jet from approximately 5 meters away, filtered by a 0.6 mm Be vacuum window, 4 m of air, and a 0.5 mm Be filter at the CCD.

In addition, two highly oriented pyrolytic graphite (HOPG) Bragg-diffraction spectrometers recorded time integrated x-ray spectra with higher resolution in a narrower spectral region. HOPG crystals operate in the mosaic focusing mode [15, 16] for high reflectivity even at multi-keV photon energies [16, 17]. The spectrometers dispersed incoming x-rays onto image plates (Fujifilm BAS-TR) filtered with 25 μm of mylar and 25 - 150 μm of Al. Previous work with Ar gas jets [11] found that the front side of the target yields cleaner spectra, and so we placed two HOPG spectrometers to observe both the front and rear sides of the gas jet, from 45 degrees below the laser axis at a distance of 22 cm. We found no significant difference in spectral quality between the two spectrometers, presumably because they were located out of the laser-target plane. Our HOPG spectra are consistent with the single hit spectra.

In the side-on view, a large format image plate based camera was operated with a 25μm Ta foil in place of a pinhole. The foil corner was positioned to cast both horizontal and vertical shadows on an image plate detector, in order to determine the source dimensions in the horizontal and the vertical directions. The camera body was constructed out of 7 mm thick Al with an interior shield of 1 mm teflon to attenuate any Al K-shell fluorescence due to hot electrons striking the camera body.

III. SPATIAL DISTRIBUTION OF Kα AND SPECTRAL COMPOSITION

We measured the spatial distribution of the Kα and Kβ emission with filtered shadowgraphy from the image plate based camera. The camera was filtered with 25 μm of Pb (to block radiation below Kr Kα and attenuate Kr Kβ due the Pb L-shell edge at 12.8 keV) and 100 μm of Al (placed between the Pb filter and the image plate to block Pb fluorescence). The 25 μm thick Ta foil was placed in the nose of the camera (instead of a pinhole), located 5.3 cm away from the center of the target chamber and 20.5 cm in front of the image plate for a magnification M = 3.9. As seen in Fig. 2 a), the shadow cast by the corner of the Ta foil captures the edge response g of the point source function (PSF) with the straight edges of the foil in x and y, the horizontal and vertical directions [18]. The spatial derivatives dg/dx and dg/dy are the associated line spread functions that represent one-dimensional integrated profiles of the point source function. A Gaussian point source function has Gaussian line spread functions, and so by assuming cylindrical symmetry we can use the two line spread functions to tomographically recreate the two-dimensional source projection visible in Fig. 2 b). We see an astigmatic source with FWHM dimensions of 1.7 x 1.0 mm, oriented along the laser axis. Finite camera alignment accuracy introduces an uncertainty in the x and y dimension measurements of $\pm12\%$ and $\pm8\%$, respectively, estimated from the variation of intensities along the edge shadows. These findings are consistent with the one-dimensional source size given via source broadening on the HOPG [16]. Previous work in Ar at lower laser intensity and energy [19] found a smaller astigmatic source of x-rays above 0.5 keV, also oriented along the laser axis.

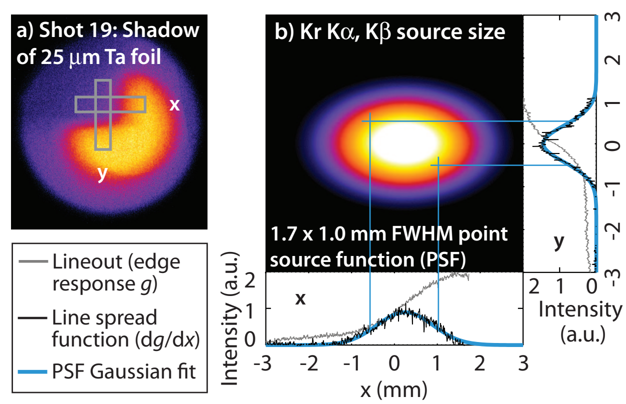

FIG. 2: (Color online) a) Filtered shadowgraph of Kr Kα and Kβ emission, b) Tomographically reconstructed x-ray source size assuming cylindrical symmetry.

The single hit spectrum shown in Fig. 3 a) shows Kr Kα at 12.6 keV and Kr Kβ at 14.1 keV with almost no background emission and an exceptionally high contrast ratio of 65. We define the contrast ratio as the ratio of the Kα line intensity to the background intensity. At 12.6 keV, the measured bandwidth from the single hit spectrum is $\Delta E/E = 2 \times 10^{-2}$, including broadening due to the single hit CCD response. After correcting for source and depth broadening [16], the bandwidth measured from the HOPG spectra is $\Delta E/E = 5 \times 10^{-3}$. Additionally, the observed Kr Kα line in both cases is broadened by emission from multiple ionization states. No highly ionized He-like x-ray line emission is visible, indicating a plasma bulk electron temperature below 1.9 keV, the ionization energy of the last Kr L-shell electron.

Simulations of the laser interaction using the 1-dimensional particle-in-cell code LPIC [20] predict a hot electron distribution with a characteristic temperature of 3 MeV for laser intensities of 10^{20} W/cm^2, as seen in Fig. 3 (b). A hot electron fraction in the entire plasma of 0.005% at 3 MeV is consistent with the relative volumes of the directly and indirectly heated plasmas. Assuming a plasma opacity length of 1 mm (i.e. the Kα source size in the vertical dimension as seen in Fig. 2) and an emission time of 10 ps [8] the spectral code FLYCHK [21] can be used to simulate the source-broadened spectrum shown in Fig. 3 (a) with bulk electron temperatures T_e ranging between 50 and 70 eV, depending on the shot. The bulk T_e is calculated separately based on the measured ratio of Kα to Kβ integrated line intensities from the single hit spectra, and is consistent with previous temperatures observed in Ar gas jets [11]. These temperatures indicate a Kr ionization state of 13-16; using the neutral density measurement we therefore have a plasma electron density $n_e = 1.1 - 1.4 \times 10^{21}$ cm^{-3} $\pm 10\%$. This analysis is valid during the Kα emission phase of the plasma evolution, i.e. before the hot electrons (and any associated return current electrons) relax below the Kr K-shell ionization threshold.

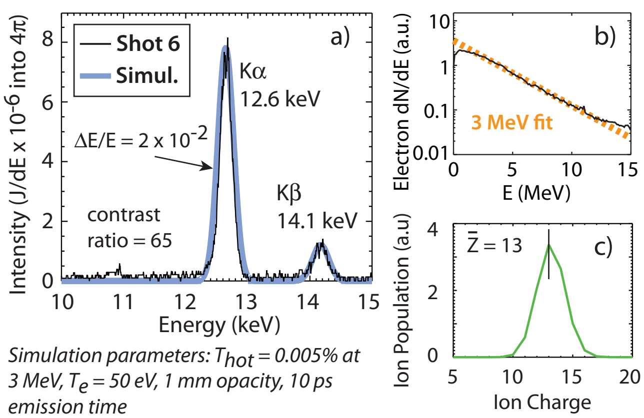

FIG. 3: (Color online) a) Time-integrated measured (single hit CCD) and simulated (FLYCHK) Kr x-ray spectra for T_e = 50 eV, b) LPIC simulated electron distribution, c) Kr ion charge at T_e = 50 eV.

IV. CONVERSION EFFICIENCY

Integration of the Kα peak shown in Fig. 3 yields the absolutely calibrated laser to Kr Kα x-ray conversion efficiency, which is up to 2.1×10^{-5} with corresponding yields of up to 1×10^{10} photons per joule of laser energy into 4π. This conversion efficiency is competitive with Kα sources produced with metal foils of similar Z in previous work [1] that showed conversion efficiency in the 10^{-5} to 10^{-4} range. Measurements of conversion efficiency and photon yield from the single hit camera have a total relative error of 30% due to uncertainty in the single hit efficiency [14] at 12.6 keV. Assuming the same integrated reflectivity at 12.6 keV as what has been previously measured for 8.6 keV [16], the HOPG spectral data confirm this conversion efficiency within the experimental error bar.

V. SUMMARY

In summary, we have shown that Kr gas jets irradiated by ultra short laser pulses are high contrast, debris-free extended sources of Kα x-rays at 12.6 keV with competitive conversion efficiency and narrow bandwidth. Such sources are suitable for area backlighting and high dynamic range scattering. Future work will investigate these applications, use time-resolved diagnostics to measure the temporal resolution available with Kr gas jet Kα sources, and model the plasma and x-ray emission in more detail.

VI. ACKNOWLEDGMENTS

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[1] H.- S. Park, D. M. Chambers et al, Phys. Plas. **13**, 056309 (2006)
[2] J. A. Cobble, T. E. Tierney, and J. Abdallah, Jr., J. Appl. Phys. **102**, 023303 (2007)
[3] O. L. Landen et al, Rev. Sci. Instrum. **72**, 627 (2001)
[4] M. K. Urry, G. Gregori, O. L. Landen, A. Pak, S. H. Glenzer, JQSRT **99**, 636 (2006)
[5] S. H. Glenzer, O. L. Landen, P. Neumayer, R. W. Lee, K. Widmann, S. W. Pollaine, and R. J. Wallace, Phys. Rev. Lett. **98**, 065002 (2007)
[6] A. L. Kritcher, P. Neumayer et al, HEDP **3**, 156 (2007)
[7] H. Chen, R. Sheperd et al, Phys. Rev. E **76**, 056402 (2007)
[8] Ch. Reich,P. Gibbon, I. Uschmann, and E. Förster, Phys. Rev. Lett. **84**, 4846 (2000)
[9] F. Y. Khattak, E. Garcia Saiz, T. Dzelzainis, D. Riley, and Z. Zhai, Appl. Phys. Lett **90**, 081502 (2007)
[10] S. H. Glenzer et al (to be published)

[11] N. L. Kugland et al, submitted to Appl. Phys. Lett. (2008)
[12] T. Ditmire et al, Phys. Rev. Lett **78**, 3121 (1997)
[13] M. Born and E. Wolf, eds., *Principles of Optics*, 5th ed. (Pergamon, New York, 1975)
[14] B. R. Maddox et al, submitted to Rev. Sci. Instrum. (2008)
[15] S. H. Glenzer et al, Phys. Rev. Lett. **90**, 175002 (2003)
[16] A. Pak et al, Rev. Sci. Instrum. **75**, 3747 (2004)
[17] T. Döppner et al, submitted to Rev. Sci. Instrum. (2008)
[18] S. W. Smith, *The Scientist & Engineer's Guide to Digital Signal Processing*, 1st ed. (California Tech. Pub, San Diego, 1997)
[19] T. Ditmire, E. T. Gumbrell, R. A. Smith, A. Djaoui, and M. H. R. Hutchinson, Phys. Rev. Lett **80**, 720 (1998)
[20] A. Kemp et al, Phys. Plasmas **11**, 5648 (2004)
[21] H. -K. Chung et al, High Energy Dens. Phys. **1**, 3 (2005)